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HYDROLOGY OF SURFACE SUPPLIES TO RUNOFF

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This report was prepared to provide information that may prove helpful in analyzing the hydrologic performance of watersheds. Information of this type is needed by members of flood control organizations. Relationships presented are based on the following concepts: (1) That an infiltration curve can be prepared for a given cover, soil, and soil-moisture content; (2) that antecedent soil-moisture content can be estimated in order that an appropriate infiltration curve may be superimposed over a storm pattern to determine surface supplies to runoff.

This report is divided into six parts as follows:

PART 1 - INTRODUCTION

Stream flow at any point in a river system is made up of surface supplies of water and subsurface flows reappearing on the surface above the point in question. Surface supplies are made up essentially of excesses of rainfall rates over infiltration rates. Interception and depression storage are considered in the derivation of such infiltration values. Since, during the storm period, the infiltration rate curve drops and approaches a reasonably constant minimum for a particular soil, the time of occurrence of excessive rainfall rates, in other words, the precipitation time pattern, is important. The capacity rate of infiltration is the rate at which infiltration would take place at any instant were the supply to equal or exceed this capacity.

The capacity or potential infiltration rate curve depends upon the cover and soil, and generally decreases as the soil-moisture content increases or when sealing occurs. Infiltration curves for various covers and soils as derived herein provide information pertaining to the basic land-use effect of small areas. In addition, such information can be applied, in principle, to different drainage systems where land use is to be changed.

The infiltration rate for a soil profile is controlled by the permeability of the layer or horizon of the soil profile where pore space has been reduced or where water moves at a minimum velocity or both. This may take place within the soil profile or at the soil surface. Much of the land at Coshocton, Ohio, is in a 4-year rotation of corn, wheat, and 2 years of meadow; or in meadow, pasture, and forest. Maintenance of such covers and the following of sound conservation practices have resulted in a fairly stable and protected soil structure. For much of the cover and practices on the soils mentioned herein, the horizon limiting infiltration is the subsoil or "B" horizon. However, particularly during storms of high intensity on corn, the limiting layer is the soil surface which seals when unprotected. It will be shown later that for unprotected soils relatively more runoff and higher rates of runoff may occur from dry rather than wet soils. For example, taking precipitation into account, relatively more runoff occurred from unprotected soils at a moisture content of 0.15 inch of water per inch of soil than from soils 0.30 inch of water per inch of soil. This indicates the effect of the slaking action referred to by Yoder (11)[1] in addition to the direct mechanical dispersion and compaction of soil mentioned by such early investigators as Wollny, as reported by Baver (1). Slaking usually occurs when very dry soils are wetted rapidly. It has been described as an explosive type of dispersion, most violent and complete when dry unprotected soils are wetted rapidly. At a soil-moisture content of 0.30 inch or greater per inch of soil, runoff from cornland was only slightly greater than runoff from wheat at the same initial soil-moisture content.

Soil moisture is frequently an excellent index of the potential infiltration rate of soils with a stable, well-protected structure. At Coshocton, soil-moisture contents were determined periodically, and

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[1]Numbers in parentheses refer to Literature Cited.

frequently before and after storms, with gypsum blocks and by field sampling (gravimetric method). Continuous soil-moisture records have been obtained for a few seasons with recording tensiometers. In lieu of direct readings of soil-moisture content, estimations may be made as mentioned later.

Before use is made of any of this information careful consideration should be given to the hydrologic characteristics of the soils. Keene silt loam and Muskingum silt loam are the soils discussed herein. In the chart compiled by H. H. Morse of the Soil Conservation Service Region 3, January 1943, Keene and Muskingum are listed as residual upland soils. Keene is described as gray-brown and moderately drained with a profile number of 3, whereas Muskingum is described as shallow and well drained with a profile number of 6.

Keene silt loam has a high percentage of silt and clay particles, particularly in the subsoil. Muskingum silt loam (sandstone origin) has a large percentage of coarse particles throughout the profile, particularly parent material fragments greater than 2 millimeters, making this soil highly porous and favorable to rapid drainage of water. The swelling properties of Keene silt loam markedly retard soil-water movements. The hygroscopic water and the minimum field soil-water are much higher in Keene silt loam than in the Muskingum soils. The water-holding capacity of both soils is about the same. Consequently, there is less available storage space in the Keene. When soils approach saturation, as they frequently do during late winter or early spring, runoff generally occurs much sooner on Keene silt loam than on the Muskingum soils. When the soils are very dry, as often happens in late summer or early fall, more storage space is available, and infiltration rates and amounts in the Keene silt loam approach those in the Muskingum soils when the soils are protected. The pore-size distribution-curves of the topsoil of Keene silt loam and Muskingum silt loam are nearly the same, whereas those of the subsoil show a great contrast in water-holding ability. In the field this is reflected in greater runoff on Keene silt loam than on Muskingum silt loam when the topsoils are near saturation and the permeability of the subsoil controls infiltration rates. The subsoil of the former holds more water at the same tension than the subsoil of the latter from which the water drains more readily. Detailed information on the profile characteristics of the soil types studied were previously presented by Dreibelbis and Post (2, 3).

PART 2 - DERIVATION OF INFILTRATION CURVES

Information contained herein on infiltration was derived mainly from Watershed 123, Keene silt loam, 1.37 acres, and from Watershed 109, Muskingum silt loam, 1.69 acres. These watersheds are in a 4-year rotation of corn, wheat, and 2 years of meadow. Rainfall was measured by recording rain gages. Runoff was composed primarily of surface flow and was measured in precalibrated flumes equipped with waterstage recorders. Hydrograph recessions, the absence of seepage around the deep walls supporting the flumes, and soil-moisture determinations indicate little, if any, subsurface lateral-flow return to the surface above the measuring flumes.

Figure 1, page 5, illustrates factors considered in developing infiltration curves. Ground rainfall, P_g, as used in the analysis, represents precipitation, P, measured in the open from which interception storage by vegetation, S_i, has been subtracted. Values for interception storage by various crops have been compiled from various sources, such as Musgrave and Norton (6). Values were corrected when they included stem flow and for local crop conditions. Interception storage plots as a curve which reaches a maximum when there has been sufficient rainfall for water to flow over the plant and into locations not exposed directly to rainfall.

The graphical method used to obtain corrections for detention storage was developed by Holtan (4) and modified by the author. It essentially uses a straight "precipitation" reference line drawn approximately parallel to the high intensity portion of the accumulated ground rainfall curve, P_g.

The next step is the development of the curve shown in **figure 1, page 5,** as "R plotted to reference line." Since S_i has already been accounted for, R (retention) includes V_d (depression storage) and F (mass infiltration). S_i was accounted for when P_g was established. To establish "R plotted to reference line," points on the accumulated-surface-runoff curve, Q_s, are selected where detention storage values, D_s, are close to zero. Such points occur where rates of runoff are close to zero. Other points on Q_s may also be selected when information exists as to the quantity of recession flow associated with a particular rate of flow. To a particular

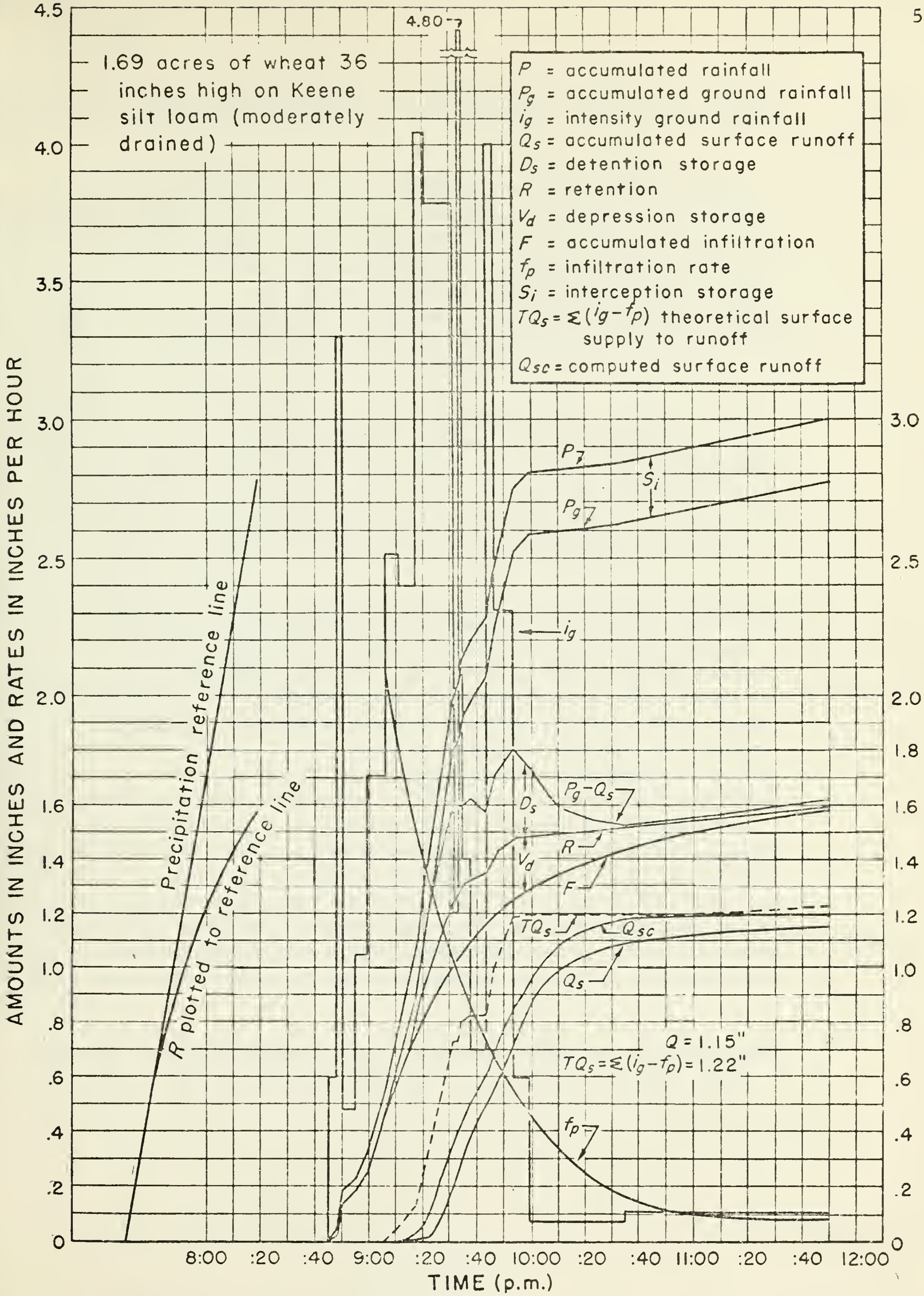

Figure 1.– Analysis of storm of June 16, 1946, for watershed 123.

Q_s associated with a trough point on a hydrograph is added the recession flow that will result from the rate of flow that exists at the trough point.

Next, the precipitation, P_g, associated with each point representing Q_s where D_s is close to zero or Q_s plus recession, is determined. The ordinate on "the precipitation reference line" is located equal to each P_g thus determined. From this is subtracted the quantity Q_s or Q_s plus recession, whichever the case may be, providing one plotting point. Sufficient points are similarly established to locate the "R plotted to reference line" curve. In other words, this line represents R with D_s eliminated.

The next step is to establish R beneath the P_g curve. The ordinate on the "precipitation reference line" directly above any selected point on the "R plotted to reference line" curve is determined. The same ordinate is located on the P_g curve. The ordinate of the selected point is placed directly below the ordinate located on the P_g curve. Sufficient points are thus located to establish the R curve.

The R curve is composed of V_d and F. Although some information exists on depression storage, corrections for this factor are largely estimations. However, such corrections may be checked by the depletion of a certain amount of depression storage over a period of time at the existing infiltration rate for this same period. Mass infiltration follows the exhaustion law and families of curves have been prepared for the various scales used in graphical analysis at Coshocton. The curve is used which best fits the points established after the above corrections have been made. The slope of the mass infiltration curve is the infiltration rate, and families of curves have been prepared corresponding to the established mass infiltration curves. Each infiltration rate curve is checked. Rainfall rates in excess of infiltration rates are determined and multiplied by their appropriate time intervals. The accumulated excess represents the surface supply to runoff and is checked against the actual measured runoff. Also, whenever possible, mass infiltration is checked against measured soil-moisture increases.

The accumulated excess, TQ_s, as obtained above, at any specific time is equal to any detention storage, D_s, that may exist plus

the accumulated supply to surface runoff Q_{sc}. The volume of water making up the computed surface runoff, Q_{sc}, up to any time is then equal to $TQ_s - D_s$. The Q_{sc}-curve is shown in figure 1, page 5, and represents the computed accumulated surface runoff. This curve is somewhat different in shape and precedes the measured accumulated surface runoff Q_s. The shape and position of the Q_s-curve represent the effect of the physiography of the watershed upon the Q_{sc}-curve. The slope of the Q_{sc}-curve represents the rate of supply of water to surface runoff on the watershed just as the slope of the Q_s-curve represents the rate of surface runoff at a specific location. Relationships between the Q_{sc}-curve and the Q_s-curve will be part of a subsequent paper now being prepared.

PART 3 - INFILTRATION CURVES FOR VARIOUS CROPS

Figures 2 and 3, pages 8 and 9, present infiltration curves for corn, wheat, and meadow on Keene silt loam and Muskingum silt loam. Each curve is related to an initial soil-moisture content. The curves shown represent the center of envelopes of families of curves plotted on a single sheet. Envelopes were established by taking the curves for a given cover and soil and first plotting the curve showing the highest infiltration rate. The curve plotted next had the second highest infiltration rate and was started at a point where its maximum infiltration rate coincided with the first curve. This process was continued until the entire family of curves for a given cover and soil were plotted. Envelopes of these curves were then established and a final curve drawn in the center of the envelopes. The spread of the envelopes is small and to avoid confusion the envelopes are not shown. The development of the infiltration curves was also partially based on the transmission rates within the soil, particularly in the high range. For most practical purposes the final curves shown may be used directly. The tendency for more abrupt drops in the infiltration curves of higher initial soil-moisture content may be due partially to entrapped air and expanded colloids.

The dashed lines, curves 1 and 2 of figures 2 and 3, pages 8 and 9, representing the infiltration rate for corn at a soil-moisture content of 0.10 and 0.20 inch of water per inch of soil, are based on the velocity or transmission rate of water and the pore space through which water moves. This method has been described by Schiff (8). When sealing occurs, such as in the case of unprotected cornland, curves 1 and 2

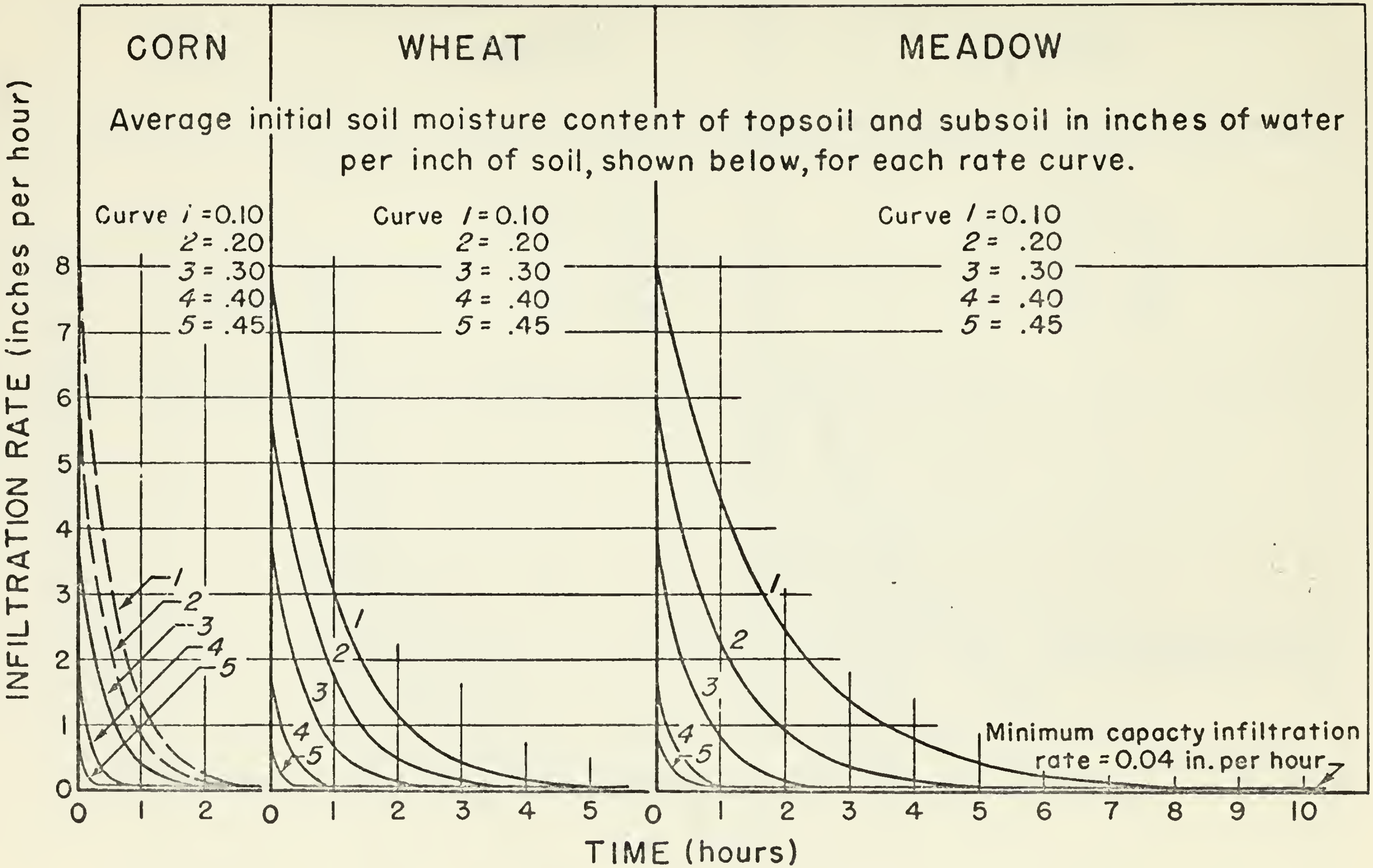

Figure 2.—Capacity infiltration rates for corn, wheat, and meadow, on Keene silt loam.

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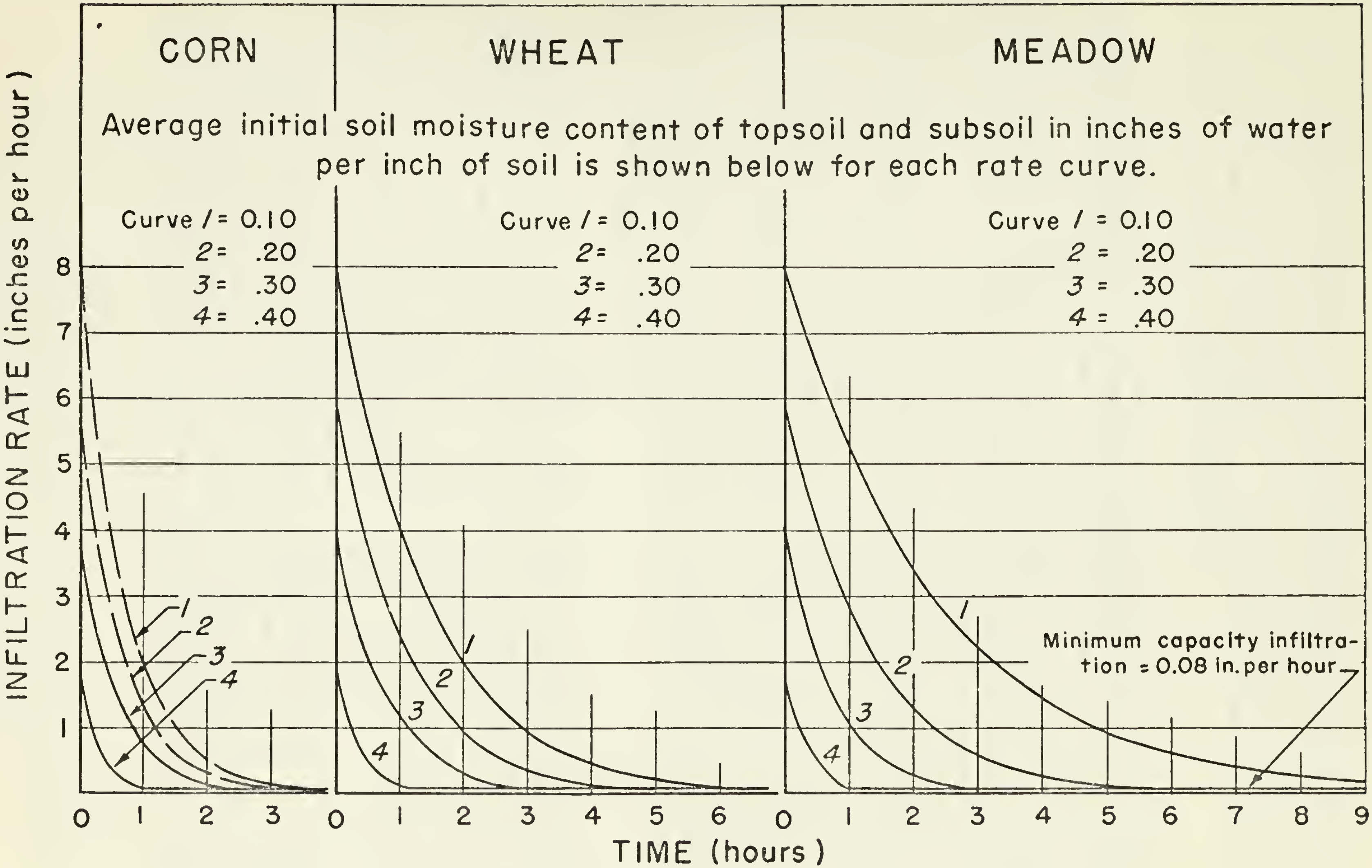

Figure 3.—Capacity infiltration rates for corn, wheat, and meadow, on Muskingum silt loam.

for corn should not be used. The sealing of the soil surface does not nullify natural laws which make permeability a function of the velocity of water which moves through a given volume of pore space. Sealing simply reduces this given volume of pore space and consequently reduces permeability. The extent to which the pore space is reduced by dispersion requires further investigation.

Figures 4(a) and 4(b), page 11, indicate the effect of sealing and provide information for the computations that deal with such conditions. The fact that the soils shown in figure 4(a), page 11, are Muskingum silt loam and Muskingum loam would cause only small differences in hydrologic performances. Curve 1 of figure 4(a), page 11, shows an infiltration rate for corn at an initial soil-moisture content of about 0.15 inch of water per inch of soil. It represents the interpolation between curves 1 and 2, for corn, of figure 3, page 9. Infiltration curve 2 of figure 4(a), page 11, is the result of the storm of June 23, 1944, on Watershed 106, unprotected corn on Muskingum loam, at an initial soil-moisture content of about 0.15. Rainfall was 1.16 inches with rates as high as 4.8 inches per hour, and runoff was 0.39 inch. The soil-moisture gain was approximately 0.77 inch, which, if considered evenly distributed in the topsoil, would increase the soil-moisture content to 0.26 inch of water per inch of soil. Normally, this soil-moisture content would result in no flow if soil moisture were the influencing condition. There was no runoff from meadow on either Keene silt loam or Muskingum silt loam.

Infiltration curve 3 of figure 4(a), page 11, is the result of the storm of August 23, 1944, also on Watershed 106, unprotected corn on Muskingum loam at an initial soil-moisture content of about 0.15 inch of water per inch of soil. The rainfall for this storm was 1.33 inches with rates of rainfall as high as 12 inches per hour. Runoff was 0.94 inch. The soil-moisture gain was approximately 0.39 inch of water, which, if considered evenly distributed in the topsoil, would increase the soil-moisture content to about 0.21 inch of water per inch of soil. Again, with ample (over 2 inches) available pore space in the topsoil, no runoff would occur without sealing. Infiltration curves (2) and (3) are almost identical. The higher intensities and amounts of rainfall during the storm of August 23, 1944, accounted for higher rates and more runoff than did the storm of June 23, 1944. Neither storm produced runoff from meadow on Keene silt loam and Muskingum silt

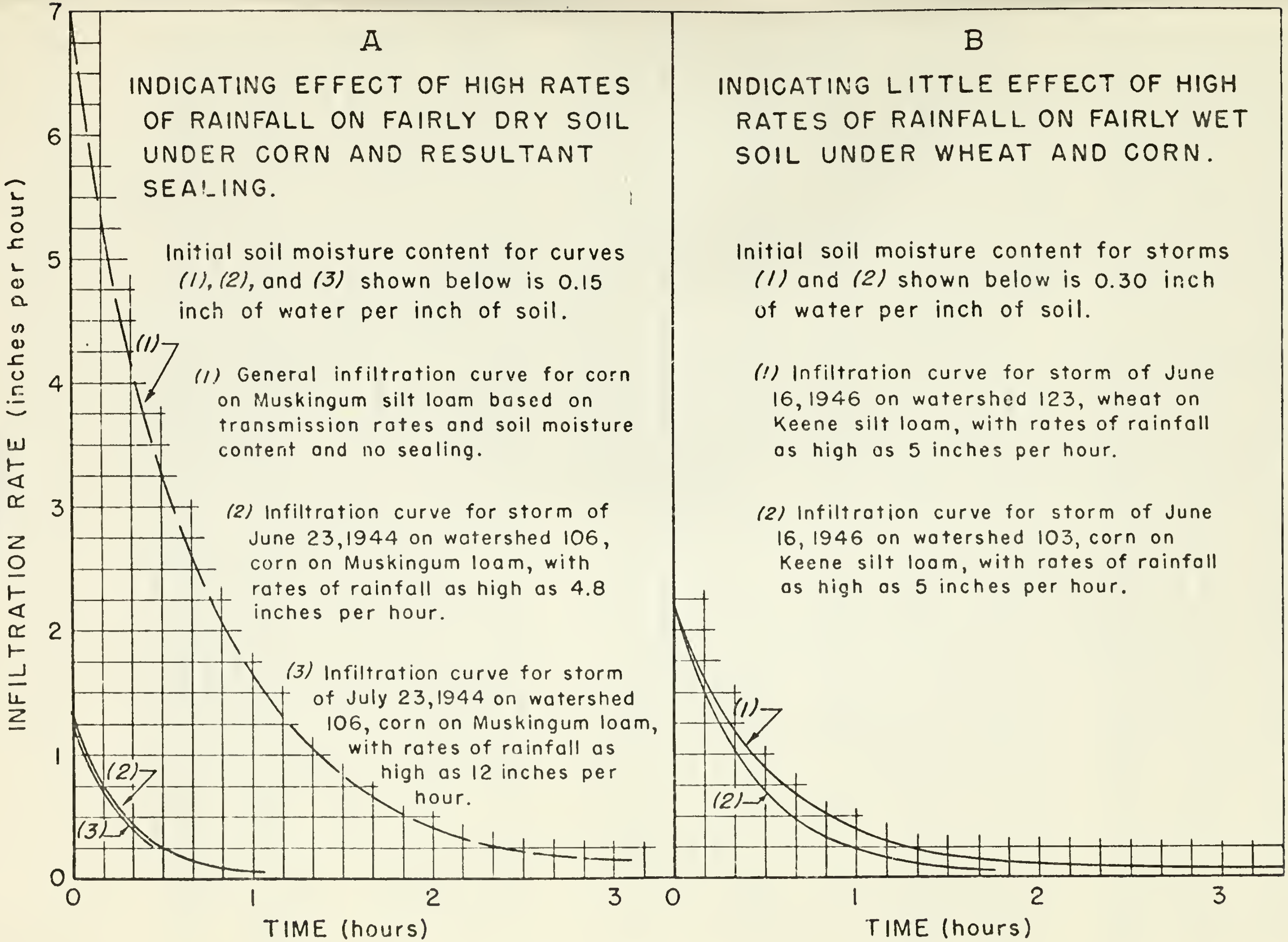

Figure 4.– Capacity infiltration rates showing effect of sealing.

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loam, where prior to the storm there were approximately 2.45 inches of pore space available to store water in the topsoil. Cornland had approximately the same pore space available to store water in the topsoil. The great difference in infiltration curves (2) and (3) when compared to curve (1) of figure 4(a), page 11, is essentially due to sealing. It is interesting to note that the infiltration rate shown in curve (1) dropped from 1.25 to 0.25 inches per hour in 70 minutes, whereas the infiltration rate shown in curve (3) dropped the same amount in 26 minutes.

Figure 4(b), page 11, represents infiltration curves derived for the storm of June 16, 1946, on Watershed 123 (wheat on Keene silt loam) and Watershed 103 (corn on Keene silt loam). The antecedent soil-moisture content was about 0.30 inch of water per inch of soil for both watersheds. Infiltration curves (1) and (2) of figure 4(b), page 11, represent capacity rates somewhat after the storm began, when the soil-moisture content was slightly higher than 0.30 inch of water per inch of soil. For the major part of the storm, rainfall amounted to approximately 3 inches and runoff was 1.1 inches from the wheat and 1.4 inches from the corn. The difference in runoff was not great and was probably due to some mechanical dispersion on the soil surface. This is also indicated by the infiltration curve (2) for corn, which is slightly under curve (1) for wheat. In this case pore space in the topsoil sufficient to store about 1.4 inches of water was completely exhausted. A slight amount of water entered the subsoil and 1.4 inches of water ran off. High soil moisture and slow water transmission into the subsoil were the major controlling factors in this storm, thus causing high runoff.

It is believed important to repeat some of the above data with an attempt at an explanation of the differences. The rain of July 23, 1944, amounted to 1.33 inches on Watershed 106 (corn on Muskingum silt loam) at a soil-moisture content of 0.15 inch of water per inch of soil and the rain of June 16, 1946, amounted to 3 inches on Watershed 103 (corn on Keene silt loam) at a soil-moisture content of 0.30. Yet the runoff for the July 23 storm amounted to 0.94 inch compared to a runoff of 1.4 inches from the June 16 storm. This represents a difference of only 0.46 inch in runoff as compared to a difference of 1.67 inches in rainfall. Only about 0.39 inch of water entered a soil with an initial moisture content of 0.15 whereas about 1.6 inches of water entered a soil with an initial soil-moisture content of 0.30. It seems that the high intensities of rainfall (in sequence, 6 inches per hour for 1 minute, 12 inches per hour for 1 minute, 6 inches per hour 1 minute) on a fairly dry soil

caused much more sealing than somewhat lower intensities (5 inches per hour for 3 minutes) on fairly wet soil.

Mechanical dispersion undoubtedly occurred on both watersheds. However, most of the difference is believed to be due to the slaking of the drier soil. Yoder (11) states that the tendency of soils to break down from clods to small aggregates under the influence of moisture changes is one of the most significant dynamic properties of soils in relation to erosion control and tillage practices. To this might be added its important hydrologic effect as indicated above. Yoder points out that lumps of air-dry soil do not slake if they are first slowly wetted by a water supply controlled by capillarity. This would correspond approximately to a soil-moisture content of about 0.30 inch of water when capillary pores of the soils mentioned herein may be considered filled. Such were the conditions during the storm of June 16, 1946, mentioned in figure 4(b), page 11, when runoff was attributed largely to the soil-moisture content of the soils and to a minor extent to the mechanical dispersion on Watershed 103 in corn.

Yoder also states that when air-dry soils are rapidly wetted, air is trapped in many passageways, particularly those of small cross-sectional dimensions. Water is drawn from the larger openings by the small capillaries since a steep gradient of capillary potential is present. The entrapped air is compressed causing a series of miniature explosions which continue until the lump is shattered into its water-stable aggregates. The important effect on sealing of such dynamic action is undoubtedly a major factor in the runoff occurring during the storm of July 23, 1944, on Watershed 106 in corn. The soil moisture is given as 0.15 inch of water per inch of soil as an average for the topsoil. Undoubtedly the soil at the immediate surface was even drier and approached the air-dry conditions mentioned. This explosive type of dispersion is described as most violent and complete on dry unprotected soils, a condition often found during dry periods on land devoted to corn and other clean-cultivated crops.

The high capacity infiltration rates associated with soils at low soil-moisture content actually occur only occasionally. This is due to the fact that storms of high intensity are very infrequent. These high capacity infiltration rates are partially based on knowledge of the transmission rates or downward velocity of soil-water and the pore space

through which water moves (10). There are limits to the maximum rates of infiltration, as they are a function of the velocity of water multiplied by the cross-sectional area of the soil pores through which water can move. The latter varies inversely with the soil-moisture content.

It is to be noted that the initial maximum infiltration rates for the covers and soils shown in figures 2 and 3, pages 8 and 9, are the same. Starting at the same soil-moisture content, the hydrologic characteristics of the topsoil or plow layer of Keene silt loam and Muskingum silt loam are about the same. This probably reflects man's influence in developing the topsoil as a medium for water movements of high velocity. The greatest difference between these two soils lies in the subsoil. The drop in infiltration rate is greatest under corn and reflects the influence of sealing of the soil surface under raindrop impact. Movement of water through the soil profile is affected by the cover and its root system and the soil. As saturation of the topsoil is approached, water movements downward become limited by the permeability of the subsoil for the soils mentioned herein. As the subsoil approaches saturation, the minimum capacity infiltration rate is approached. This minimum rate is largely a function of the subsoil characteristics, as crops appear to have little effect, particularly below the major root zone. Also, the area below the major zone is little influenced by man.

The soil and deeper root zone of forests present a different condition which is reflected in infiltration rates. Figure 5, page 15, presents estimated infiltration rates for forest on Keene silt loam and Muskingum silt loam. Data used in these estimates come largely from infiltration for a forest on a Muskingum loam area and transmission rates obtained by tests on soil core samples from this area. Ratios of velocities obtained from core sampling on Keene silt loam and Muskingum silt loam under cultivated crops to Muskingum loam under forest were used to adjust infiltration curves on Muskingum loam to Keene silt loam and Muskingum silt loam. The core sampling work has been mentioned by Schiff and Dreibelbis (9).

No attempt should be made to compare forest infiltration curves of figure 5, page 15, with meadow infiltration curves of figures 2 and 3, pages 8 and 9. The data for meadow were obtained from watersheds in a 4-year rotation of corn, wheat, and 2 years of meadow as mentioned previously. There are indications that the effect of meadow in a rotation

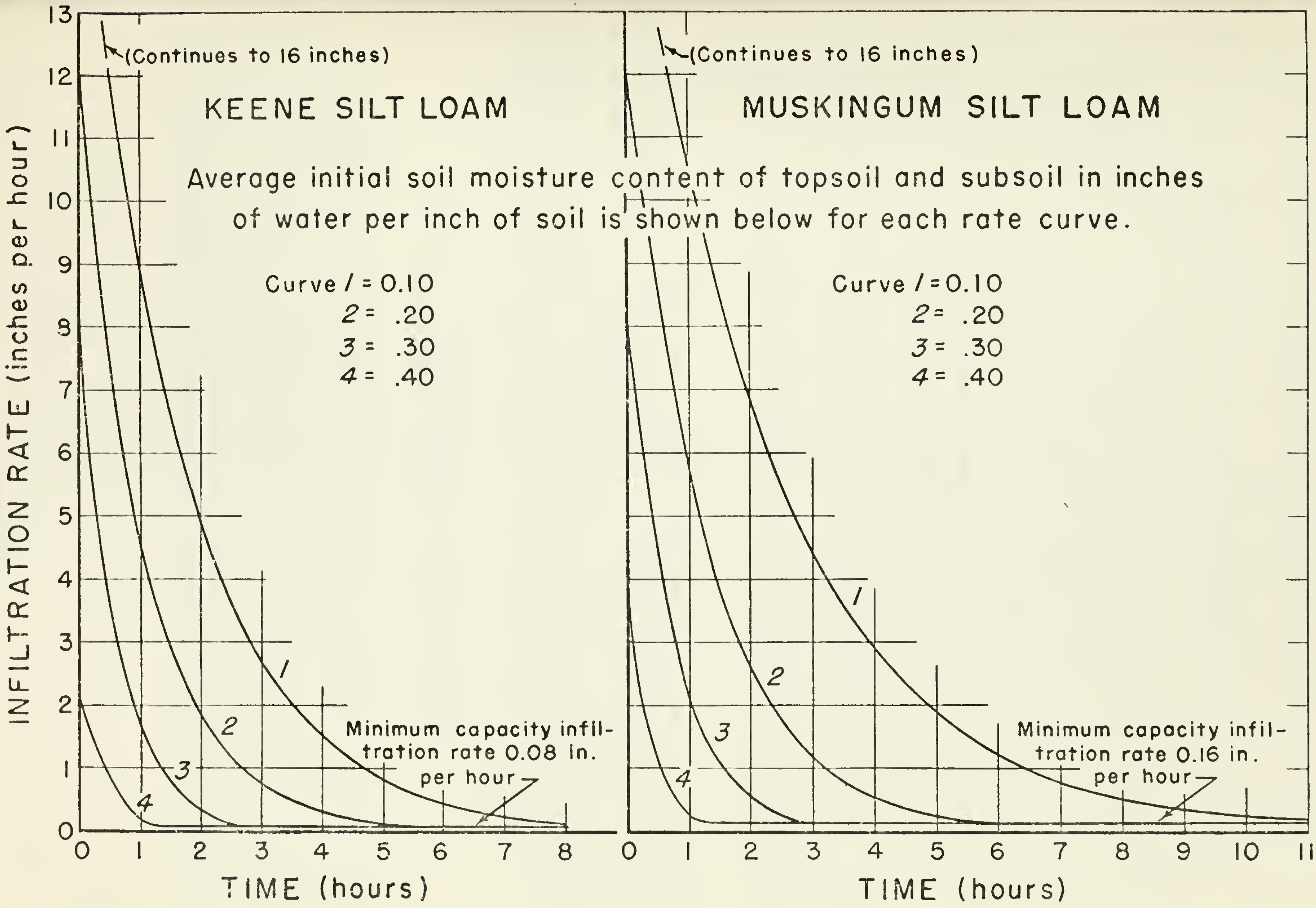

Figure 5.—Estimated capacity infiltration rates for forest.

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is somewhat modified by other crops, particularly corn. Infiltration rates for meadow and forest are frequently controlled by permeability conditions below the surface soil. Roots and residues, biological channels, and cleavage lines are probably more effective in promoting a higher rate of infiltration in a forest than in a meadow, particularly below the surface soil. Hydrograph analyses and tests of soil cores indicate this to be true for soils found at Coshocton. Permanent meadow is likely to produce somewhat higher infiltration rates than meadow in a rotation. However, data from permanent meadow on small natural watersheds at Coshocton indicate that infiltration rates are not as high under such cover as under forests. For the storm of June 16, 1946, on fairly similar soils with reasonably similar antecedent conditions, the rate of runoff from permanent meadow was 1.45 inches per hour as compared to 0.18 inch per hour from forest. This storm produced the highest rate of runoff from both forest and meadow. A reasonable estimate of infiltration rates for permanent meadow would seem to be about midway between the values shown for rotation meadow and forest. An additional point in connection with the benefits of dense vegetal cover, such as grass or forest, in reducing runoff is that the soil beneath these covers does not become wet as often as do the soils under thin vegetal covers, such as corn.

As previously mentioned, Keene and Muskingum soils are listed in the chart compiled by H. H. Morse. It should be possible, using the infiltration rate curves contained herein and other information on infiltration, to estimate infiltration curves for other soils. Soils could then be grouped hydrologically. These groupings could be modified as information develops. Such information associated with the storm patterns that occur in various localities would be of service to hydrologists.

PART 4 - ANTECEDENT SOIL MOISTURE AND SOIL-MOISTURE DEPLETION

Information given below may be helpful in estimating the soil-moisture content of soil prior to a storm. Obviously, direct measurements of the soil-moisture content is best but such data are frequently unavailable. The average seasonal soil-moisture content for each day for Keene silt loam and Muskingum silt loam is shown in figures 6 and 7, pages 17, and 18, data by F. R. Dreibelbis. This is based on 6 years of record. The curves represent the average soil-moisture content in 40 inches of

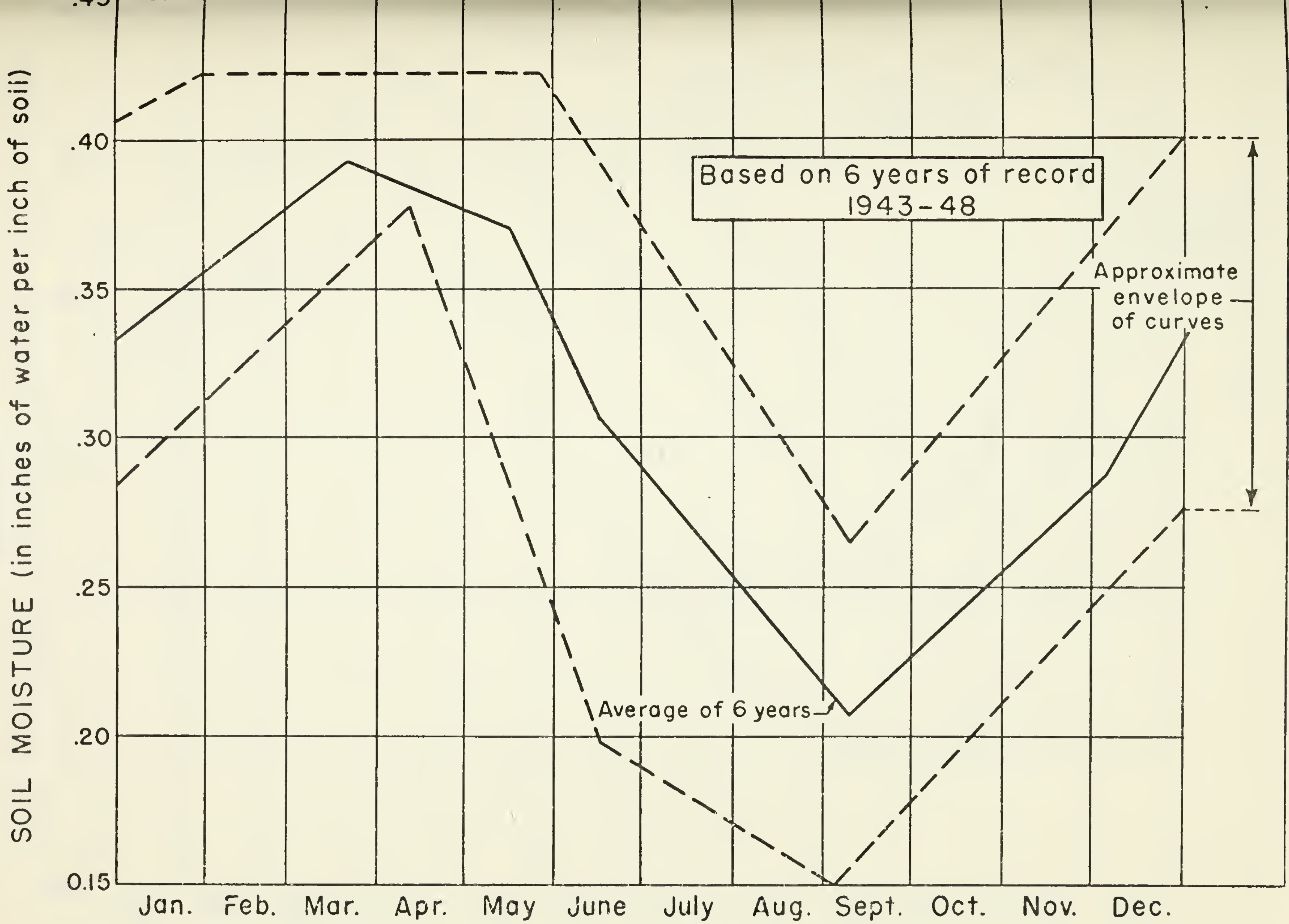

Figure 6.–Seasonal soil-moisture content, Keene silt loam.

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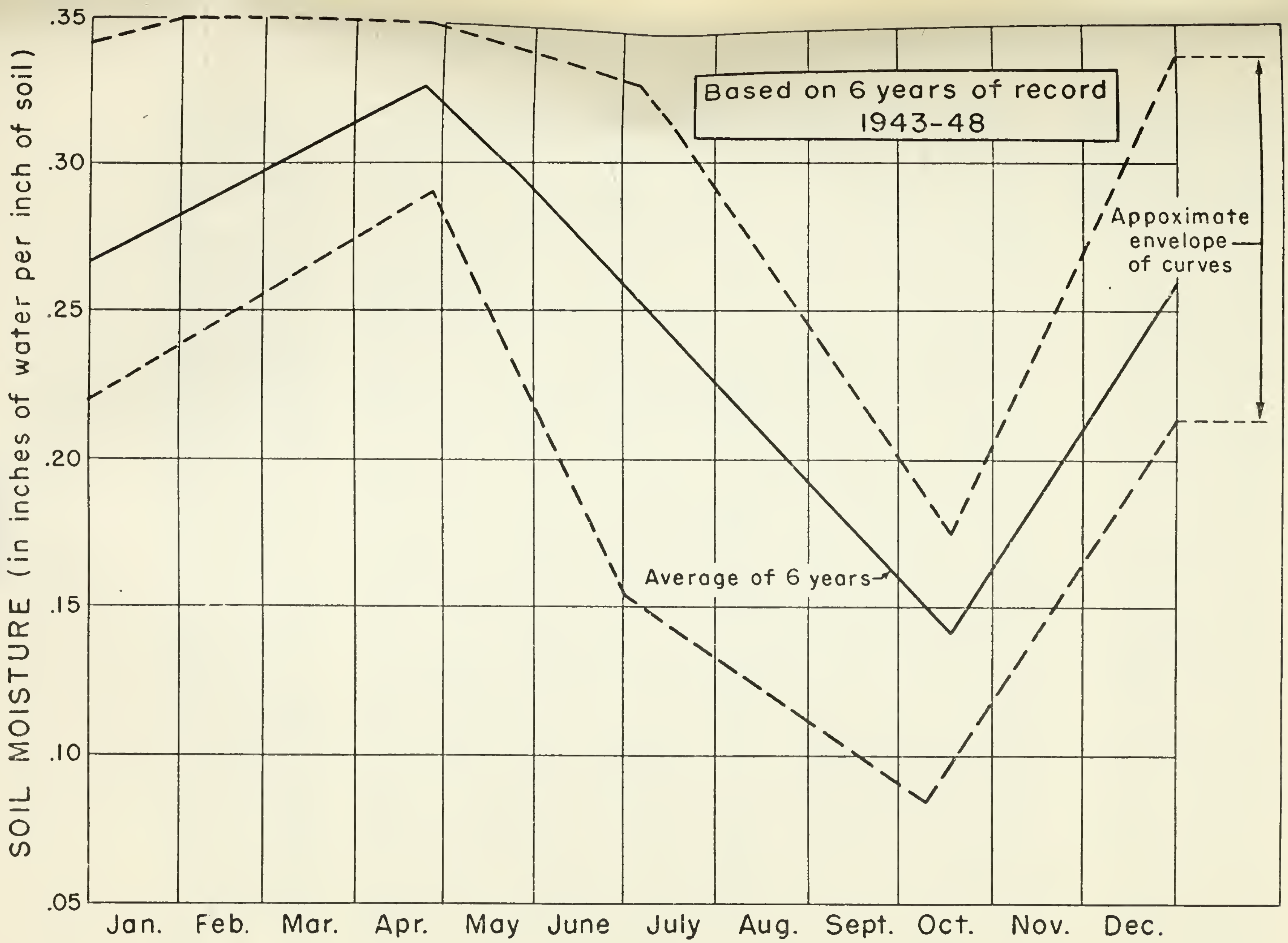

Figure 7.–Seasonal soil-moisture content, Muskingum silt loam.

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soil profile. Generally, during flood flows, the soil profile is wet to considerable depth and some limiting condition such as pore size and moisture content in a portion of the profile or the entire profile may function in regulating the infiltration rate. These figures give an indication of the antecedent soil-moisture content which is helpful in the selection of the appropriate infiltration curve to be used in estimating supplies to surface runoff.

More information may exist on rainfall antecedent to a storm and another method may then be used to estimate the soil-moisture content. Usually storms producing high flows are preceded by rains which wet the soil. It is reasonable to assume that soils will be nearly saturated by such antecedent rainfall. Assuming saturation of the soil by antecedent rainfall the next step is to determine the soil-moisture depletion that takes place in the time interval between the end of such antecedent rainfall and the portion of the storm producing the flow in question. Figure 8, page 20, data by F. R. Dreibelbis, has been provided for that purpose. Starting from saturation, which is about 0.50 inch of water per inch of soil for both Keene silt loam and Muskingum silt loam the soil-moisture content, as depletion takes place, is shown for various intervals of time. These curves are based on 14 inches of soil profile for various crops. Above field capacity the curves may be applied directly, as percolation is the major depleting factor. The crop is the major depleting factor after field capacity is reached, when depletion results entirely from evapo-transpiration. Table 1, page 21, provides soil-moisture depletion values below field capacity for various crops showing seasonal effects. For reasonably similar conditions it is believed that these curves may be used directly to represent the moisture content of the soil profile. For example, 24 hours after saturation the soil-moisture content is 0.41 for Keene silt loam and 0.34 for Muskingum silt loam. The infiltration curves for such soil-moisture contents may be selected directly or interpolated when necessary from figures 2, 3, and 5, pages 8, 9, and 15, or adjustments made for sealing based on figure 4, page 11.

There is the case when it is desired to establish the soil-moisture content when saturation is not reached under antecedent rainfall. It is then necessary to determine the soil-moisture content prior to the antecedent rainfall, the increase due to the antecedent rainfall, and the soil-moisture depletion in the interval between the antecednet rainfall and the storm in question. The soil-moisture

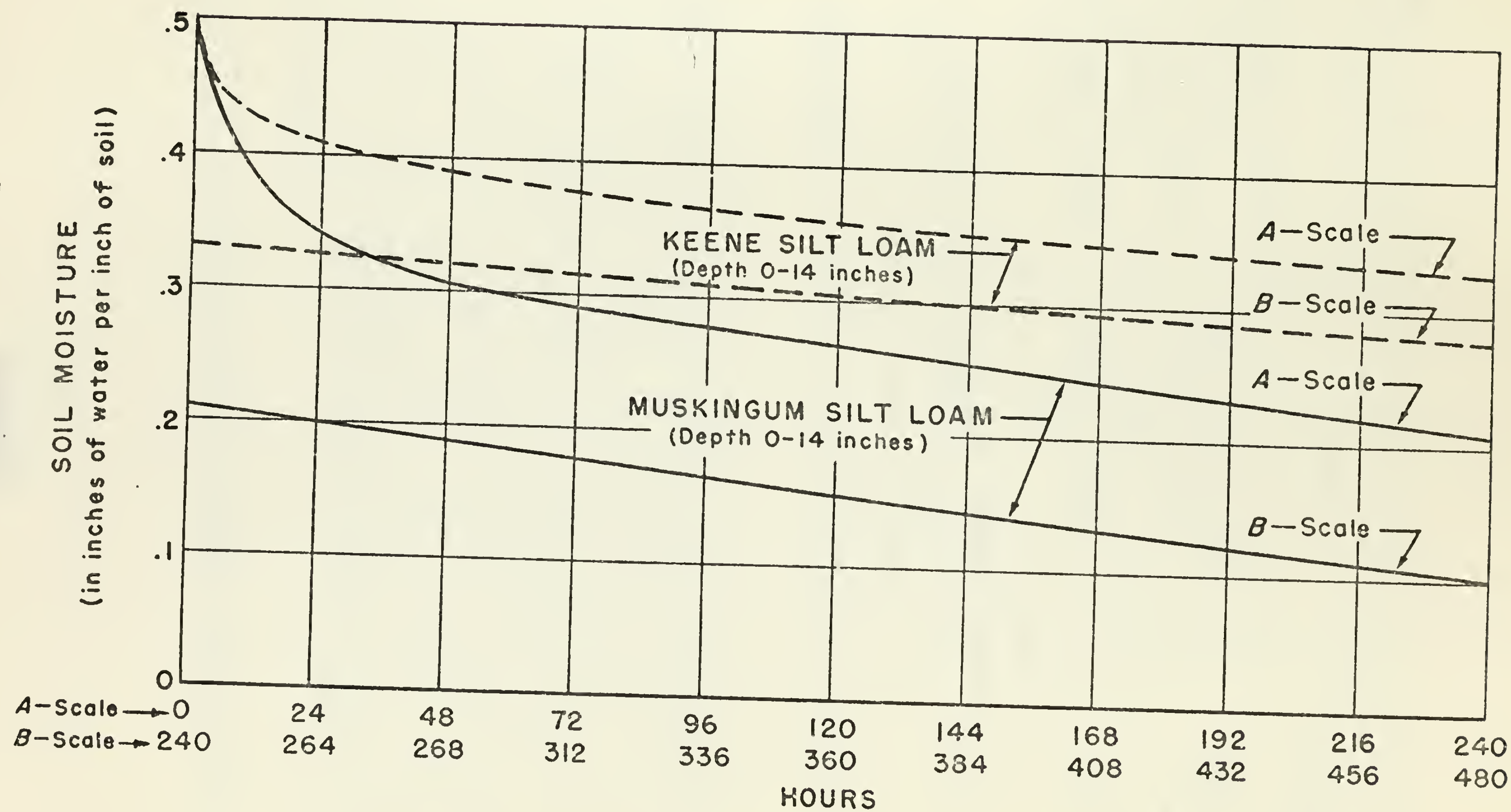

Figure 8.—Soil-moisture depletion, from saturation downward.

TABLE 1.--*Rate of soil-moisture depletion below field capacity by seasons*[1]

Crop	Season	Factor to be applied to figure 8
Corn,[2] wheat, meadow, and pasture[3]	Mav through August	100 percent
Corn,[2] wheat, meadow, and pasture[3]	April, September, October	75 percent
Corn,[2] wheat, meadow, and pasture[3]	November through March	25 percent

[1]Data in more detail will appear in proposed USDA Technical Bulletin by L. L. Harrold and F. R. Dreibelbis.

[2]Corn in period May and June, use 65 percent.

[3]For pasture of bluegrass or poverty-grass type in period May-August, use 75 percent.

content prior to the antecedent rainfall may be taken from figures 6 and 7, pages 17 and 18, if no direct and more exact information exists. For example, from figures 6 and 7, Keene silt loam is 0.39 inch of water per inch of soil and Muskingum silt loam is 0.31 on March 21. Assume an antecedent rainfall of 4 inches distributed uniformly in 40 inches of profile which represents a gain of 0.10 inch of water per inch of soil. Keene silt loam would then be 0.49 and Muskingum silt loam 0.41. Distribution of antecedent rainfall should be based on knowledge of soil-water movements in the soil considered. If there is a 24-hour period of no rain prior to the storm in question, figure 8, page 20, will indicate the depletion that will occur. In such a period Keene silt loam drops from 0.49 to 0.41 and Muskingum silt loam from 0.41 to 0.33. The values 0.41 and 0.33 would be the initial soil-moisture contents to be used in selecting infiltration curves for Keene silt loam and Muskingum silt loam, respectively.

It is interesting to note in figure 8, page 20, that differences between Keene silt loam and Muskingum silt loam range from 0.07 to 0.11

after the first 24 hours of drainage. These differences are reasonably consistent with the differences shown between the two soils in figures 6 and 7, pages 17 and 18. It is this difference in antecedent soil-moisture content that partially accounts for the difference in the runoff between Keene silt loam and Muskingum silt loam. Keene silt loam, particularly in the subsoil, has a greater amount of soil colloids than Muskingum silt loam. Swelling tends to reduce the pore space through which water can move in the former more than the latter. A difference of 0.10 inch of pore space per inch of soil would represent 4 more inches of storage space in Muskingum silt loam in 40 inches of profile. Four more inches could readily account for little surface supply of water to flood flows from Muskingum silt loam compared to flood supplies from Keene silt loam.

PART 5 - THE EFFECT OF STORM PATTERNS

The previous section dealt with the selection of capacity rate infiltration curves. High flows usually are produced by storms which exceed the capacity rates represented by infiltration curves. Obviously, because of the shape of the infiltration rate curve the sequence of occurrence of intensities during a storm is important. This timing has been referred to as "patterns" by Horner and Jens (5) and Schiff (7). For example, if the high intensities occur early in a storm it may be called an advanced pattern. Obviously, such intensities occur when the soil-moisture content is lower than it will be later in the storm. Associated with the lower soil-moisture content is a higher rate of infiltration on protected soils. If the intensities fall near the end of a storm--a delayed pattern--the soil-moisture content will have increased under the earlier lower rainfall intensities. Subsequent infiltration rates will be lower due to the higher soil-moisture content and the delayed high rainfall intensities will cause greater runoff. Other storm patterns fall between the advanced and delayed types. When sealing is the major factor causing runoff curves 2 and 3 shown in figure 4, page 11, should be used. These curves are largely independent of the soil-moisture content. In some cases the watershed condition may lie somewhere between the two extreme curves 1 and 3 of figure 4(a) and interpolation may be necessary. The effect of advanced and delayed storm patterns are discussed in detail by Schiff (8). For purposes of this paper, it is enough to say that supplies to surface runoff may be determined by superimposing these patterns over infiltration curves.

PART 6 - SURFACE SUPPLIES TO RUNOFF

Surface supplies to runoff are obtained by simply accumulating the excesses of rainfall rates over infiltration rates. The method used in obtaining the infiltration rates accounts for interception storage, depression storage, and mass infiltration. Excesses are the supply to detention storage which is the overland flow or supplies to surface runoff. Obviously, excesses can be produced only when rainfall rates exceed the infiltration rates. Each rainfall rate in excess of the infiltration rate is considered for the period of time it exists. If the period is short the average infiltration rate for the period may be used. A long period may be divided into parts in order that an average infiltration rate for each part may be used. The infiltration rate is subtracted from the rainfall rate for a given period. This amount is then multiplied by the duration of the given period in minutes divided by 60, when all units are in inches per hour. This final amount is the surface supply to runoff in inches. The accumulated excesses for the various periods represent the total surface supply to runoff. For example, in figure 1, page 5, excesses begin at 9:06 p. m. and the theoretical total supply to runoff, shown as TQ_s, is computed as follows:

$$(2.52 - 1.96) \times 5/60 + (2.40 - 1.65) \times 6/60 + (4.05 - 1.44 \times 4/60,$$

and so on = 1.22 inches at 11.50 p. m. The actual surface runoff, Q_s, as measured by a flume was equal to 1.15 inches. No excess is produced during a period in which the rainfall rate is less than the infiltration rate.

Soil-moisture depletion takes place during the periods of no rainfall in an intermittent storm, or, for that matter, during periods where depletion exceeds the supply due to rainfall. During such periods the potential infiltration rates increase, or, it may be said, there are recoveries in the potential infiltration rates. The change in soil-moisture content for such periods may be estimated from figure 8, page 20. An infiltration curve may be selected based on the antecedent soil-moisture content for each of the rainfall periods in an intermittent storm.

Supplies to surface runoff may then be estimated for the rainfall periods composing a storm. The periods of time during which rainfall rates are less than infiltration rates in figure 1, page 5, are insufficient to cause recoveries or increases in the potential infiltration rates.

The method of analysis used in **figure 1, page 5,** will reveal such recoveries when they occur.

Differences between the TQ_s and Q_s curves of figure 1, page 5, are interesting. For example, there is an abrupt rise in the TQ_s curve as compared to the more gradual start of the Q_s curve. The TQ_s curve represents an excess created "in place" over the entire watershed, whereas the initial supply to the Q_s curve frequently comes from the area in the immediate vicinity of the flume. Obviously, the lag prevails throughout the runoff period as does the ironing out of the increments of water supply. These differences reflect the influence of the physical factors of the surface of the watershed upon the movement of the water supply to the measuring flume, where it is measured as surface runoff.

It must be borne in mind that such an approach yields an "in place" supply of water to the soil surface. This "in place" supply may then be translated into the hydrograph of stream flow for a given sub-basin. The hydrographs for the sub-basins may be combined for the entire basin. This translation involves surface detention and channel storage computations. Estimates of the actual flow at any point must consider subsurface flow where such flow is appreciable. Such information should also be of value in the unit hydrograph approach.

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